TeV Emission by Ultra-High Energy Cosmic Rays in Nearby, Dormant AGNs

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The curvature radiation produced by particles accelerating near the event horizon of a spinning supermassive black hole, threaded by externally supported magnetic field lines is considered. It is shown that light nuclei suffer catastrophic curvature losses that limit the maximum energy they can attain to values well below that imposed by the maximum potential difference induced by the black hole dynamo, unless the curvature radius of magnetic field lines largely exceeds the gravitational radius. It is further shown that the dominant fraction of the rotational energy extracted from the black hole is radiated in the TeV band. Given the observed flux of ultra-high energy cosmic rays, and the estimated number of nearby supermassive black holes, it is expected that if dormant AGNs are the sources of UHECRs, as proposed recently by Boldt & Ghosh, then they should also be detectable at TeV energies by present TeV experiments.

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Energy losses resulting from interactions with the cosmic microwave background limit the distance a cosmic ray (CR) of energy $> 10^{20}$ eV can traverse to less than 50 Mpc [1]. As a consequence, if the origin of the ultra-high energy cosmic rays (UHECRs) observed is associated with astrophysical objects, rather than decaying supermassive X particles as in the top-down scenario [2], then the sources of UHECRs must be close by. Plausible classes of UHECR sources have been discussed in the literature, including active galactic nuclei (AGNs) [3] and gamma-ray bursts [4].

Recently, it has been proposed [5] that the UHECR observed at Earth may originate from dormant AGNs in the local Universe having masses in excess of $10^9 M_\odot$. The idea being that these objects, although underluminous relative to active quasars, contain spinning supermassive black holes that, instead of producing luminous radio jets as seen in blazars, serve as accelerators of a small number of particles to ultra-high energies. The acceleration mechanism invoked is associated with a BZ type process [6]; specifically, individual particles are accelerated by the potential difference induced by the rotation of a black hole that is threaded by externally produced magnetic field lines, during episodes when breakdown of the vacuum does not occur. In the absence of energy losses, the maximum energy a particle can gain by this mechanism is limited to the voltage drop involved, and is proportional to the product of the black hole mass and the strength of magnetic field.

A recent analysis [7] indicates that massive dark objects (MDOs) are present in the centers of nearby galaxies, some of which have masses in excess of $10^{10} M_\odot$. A plausible interpretation is that the MDOs are supermassive black holes, and may represent quasar remnants or dormant AGNs. This interpretation is further supported by the fact that a correlation between the black hole mass and bulge luminosity, similar to that found for the sample of galaxies studied in ref. [7], has been found [8] for a sample of bright quasars, using a completely different method. By applying their model to a list of objects from ref. [7], of which 14 have compact central masses larger than $10^9 M_\odot$, Boldt & Ghosh [5] estimate that protons can be accelerated up to energies in excess of a few times 10^{20} eV. As emphasized by them, in order to account for the measured flux of UHECRs, an average power of only $\sim 10^{42}$ erg s^{-1} is needed to be extracted from a black hole by the accelerated cosmic rays, corresponding to a mass loss rate of order 10^{10} g s^{-1}, and a loss rate of electric charge that constitutes only a small fraction of the total effective current required to induce the potential difference across the gap.

Acceleration to the maximum energy allowed is possible provided that radiative losses are sufficiently small. Boldt & Ghosh [5] argued that proton energy losses during the acceleration phase due to pair production and photomeson production on ambient photons are unimportant by virtue of the low accretion luminosity anticipated in those objects. However, they have not discussed the radiation associated with the acceleration process itself. In the following, we consider the curvature radiation produced by the accelerated particles, and show that in the case of light nuclei it limits the maximum energy attainable to values below the full voltage, unless the average radius of curvature of the particle's trajectory exceeds the gravitational radius by at least a factor of a few. We further show that the curvature radiation is emitted predominantly in the TeV band, and conclude that if dormant AGNs are indeed the sources of UHECRs, then they should also be detectable by present, ground based experiments at TeV energies.

Curvature radiation: The electric potential difference generated by a maximally rotating black hole of mass $M = 10^9 M_9 M_\odot$, threaded by magnetic field of strength $B = 10^4 B_4$ Gauss is [9]

$$\Delta V \sim 4.4 \times 10^{20} B_4 M_9 (h/R_g)^2 \quad \text{volts}, \tag{1}$$

where h is the gap height, and $R_g = GM/c^2$ is the gravitational radius. In the presence of a nonuniform magnetic field, particles accelerated by this potential difference will suffer energy losses through curvature radiation, even if initially they move along magnetic field lines. Since the gyroradius of a proton having energy ϵ, $R_c = \epsilon/eB$, is smaller than the gravitational radius:

$$R_c/R_g = (\epsilon/e\Delta V)e\Delta V c^2/(eGBM) \simeq (\epsilon/e\Delta V) < 1, \tag{2}$$

(the gyroradius of an ion of charge Z having energy near the maximum imposed by the voltage drop will be larger by a factor of Z), we expect the average radius of curvature of a particle's trajectory to be of order the curvature radius of magnetic field lines in the gap. (The curvature radii of different trajectories should span some range though, reflecting the different boundary conditions.) The computations of particles' trajectories, even for relatively simple magnetic field topologies, are complicated by the fact that the gyroradius at the highest energies is comparable to the size of the hole, as can be seen from eq. (2), and are beyond the scope of this paper. In what follows, we denote by ρ the average curvature radius of an accelerating ion, and assume that it is independent of the ion energy. The rate of energy loss through curvature radiation by a particle of energy $\epsilon = mc^2\gamma$ can then be expressed as

$$P = \frac{2}{3}\frac{e^2 c\gamma^4}{\rho^2}. \tag{3}$$

The energy change per unit length of an accelerating ion having charge Z and mass $m_i = \mu m_p$ is given by

$$d\epsilon/ds = eZ\Delta V/h - P/c, \tag{4}$$

yielding a maximum acceleration energy,

$$\epsilon_{max} = 3 \times 10^{19} \mu Z^{1/4} M_9^{1/2} B_4^{1/4} (\rho^2 h/R_g^3)^{1/4} \quad \text{eV}, \tag{5}$$

where eq. (3) has been used. Consequently, only a fraction

$$\eta = 0.1 \mu M_9^{-1/2} (ZB_4)^{-3/4} (\rho/R_g)^{1/2} (h/R_g)^{-7/4}; \qquad \eta \leq 1, \tag{6}$$

of the potential energy available will be released as UHECRs; the rest will be radiated in the form of curvature photons. For the most massive MDOs listed in table 2 of ref. [7] ($M_9 > 20$) we obtain $\epsilon_{max} \sim 1.5 \times 10^{20} \mu (ZB_4 \rho^2 h/R_g^3)^{1/4}$ eV, and $\eta \sim 0.02 \mu (ZB_4)^{-3/4} (\rho/R_g)^{1/2} (h/R_g)^{-7/4}$. Thus $B_4 \rho^2 h/R_g^3 \geq 20$ is required in order to accelerate a proton ($Z = \mu = 1$) to energies $\geq 3 \times 10^{20}$ eV in these systems, corresponding to $\eta = 10^{-3} (\rho/R_g)^2 (h/R_g)^{-1}$. The requirement on heavier nuclei is more relaxed. Estimates of the maximum value of the horizon threading magnetic field strength yield $B_4 \leq 1$ [9], and according to recent numerical simulations B_4 may be well below unity [10]. Consequently, acceleration of light nuclei to the highest energies measured by current experiments requires ρ to be larger than R_g by a factor of at least a few (assuming $h \sim R_g$). The values of B_4 obtained by Boldt & Ghosh [5] for the Magorian et al. sample [7], assuming equipartition between the magnetic field in the vicinity of the horizon and the matter infalling into the center, lie in the range between 0.1 to 1, given the estimated mass loss rate of the galaxy bulge.

The spectrum produced by the curvature radiation of a single ion will peak at an energy

$$\epsilon_{\gamma max} = 1.5 \gamma^3 \hbar c/\rho = 1.6 \times 10^{-7} \epsilon_{max} \mu^{-1} (ZB_4)^{1/2} (h/R_g)^{1/2} = 5 M_9^{1/2} (ZB_4)^{3/4} (\rho^2 h^3/R_g^5)^{1/4} \quad \text{TeV}, \tag{7}$$

and is a power law $I(\epsilon_\gamma) \propto (\epsilon_\gamma)^{1/3}$ below the cutoff. The overall spectrum of curvature photons would depend on the energy distribution of the accelerating particles, and is expected to be somewhat softer below the peak. For $\epsilon_{max} = 3 \times 10^{20}$ eV and $h \sim R_g$ we obtain from eq. (7), $\epsilon_{\gamma max} \simeq 50 \mu^{-1} (ZB_4)^{1/2}$ TeV.

The number of TeV photons per proton produced in the process is roughly

$$n_\gamma \sim eZ\Delta V/\epsilon_{\gamma max} = 10^8 M_9^{1/2} (ZB_4)^{1/4} (h/R_g)^{5/4} (\rho/R_g)^{-1/2}. \tag{8}$$

The mean free path to pair creation of a photon moving at an angle χ to the magnetic field is $l \simeq 95 (B_4 \sin\chi)^{-1} e^q$, with $q = 1.3 \times 10^3 M_9^{-1/2} B_4^{-7/4} \sin\chi^{-1} (\rho^2 h^3/R_g^5)^{-1/4}$ and, therefore, the radiated photons escape the system freely for the range of parameters considered here. However, when q becomes sufficiently small (at q of about 50 one photon per proton will be converted into an electron-positron pair), a pair cascade may be initiated with high enough probability to lead to a breakdown of the gap.

Observational consequences: As shown recently [11], the observed CR spectrum above 10^{19} eV, as measured by the AGASA [12] and Fly's Eye [13] experiments, can be accounted for by a homogeneous cosmological distribution of CR sources with power law spectra and energy production rate of 1.5×10^{37} ergs Mpc^{-3} s^{-1}. Given this energy production rate, and denoting by n_{CR} the density of objects contributing to the observed CR flux in this energy range, the average power released in the form of UHECR by a single source can be expressed as

$$L_{CR} = 2 \times 10^{42} \left(\frac{n_{CR}}{10^{-4} Mpc^{-3}} \right)^{-1} \quad \text{erg s}^{-1}. \tag{9}$$

Employing eq. (9), one finds that the average TeV flux emitted by a single CR source at a distance of $D = 50 D_{50}$ Mpc is

$$F_\gamma \simeq 10^{-12} \left(\frac{n_{CR}}{10^{-4} Mpc^{-3}} \right)^{-1} \eta^{-1} D_{50}^{-2} \quad \text{erg cm}^{-2} \text{ s}^{-1}, \tag{10}$$

where $\eta < 1$ is the UHECR production efficiency defined in eq. (6). As seen from eq. (6), η should be of order unity if the particles accelerated by the black hole dynamo are predominantly heavy nuclei. There is, however, evidence that the CR composition changes from heavy nuclei below the ankle (at energy of $\sim 5 \times 10^{18}$ eV) to light nuclei above it [12]. Assuming a protonic CR composition above the ankle, we obtain values of η between 10^{-1} and 10^{-3} for the range of parameters considered above.

The density of black holes above a certain mass can be estimated using the correlation between bulge luminosity and MDO mass found by Magorian et al. [7], and an appropriate luminosity function of nearby galaxies to correct for the incompleteness of their sample. However, as seen from eq. (5), the maximum energy a particle can attain depends on a combination of parameters and not solely on the mass. Therefore, the black hole mass above which particles can accelerate to the required energies is uncertain, and since the MDOs having relevant masses lie on the bright end of the luminosity function, this uncertainty in mass translates to a large uncertainty in n_{CR}. For a reasonable choice of parameters we anticipate that M_9 of at least a few would be required in order to account for UHECR energies observed. Using the luminosity function measured by Efstathiou et al. [14], we estimate that the density of MDOs having masses $M_9 > 1$ is of order a few times 10^{-4} Mpc^{-3}. An estimate based on a k-band luminosity function measured more recently [15] yielded a similar value.

The threshold flux for a 5σ detection of gamma-rays above TeV by current TeV experiments is $\sim 5 \times 10^{-12} t_{day}^{-1/2}$ erg s^{-1} cm $^{-2}$, where t_{day} is the exposure time measured in days [16]. With the above estimation of η and n_{CR}, we expect that at least some fraction of the UHECR sources will be detectable by present TeV experiments, provided that the TeV photons escape the system. Conceivable sources of opacity that may give rise to attenuation of the TeV flux are considered next.

The curvature photons produced near the black hole can be absorbed through pair production on IR photons in the galaxy. The corresponding optical depth at a given energy depends on the spectrum of IR photons and the energy dependence of the cross section. To an order of magnitude it is given by, $\tau_{\gamma\gamma} \simeq \sigma_{PP} n_{IR} R$, where R is the size of IR emission region - of order several kpc as inferred from the light profiles, n_{IR} is the number density of IR photons, and σ_{PP} is the pair production cross section, given approximately by $\sigma_{PP} \simeq 0.2\sigma_T$ at energies near the threshold. Using this approximation one finds that TeV photons would escape the galaxy provided that the IR luminosity at energy $\epsilon_{IR} = (m_e c^2)^2/\epsilon_\gamma$ satisfies:

$$L_{IR}(\epsilon_\gamma^{-1}) < 3 \times 10^{45} \left(\frac{R}{3\ \mathrm{kpc}}\right) \left(\frac{\epsilon_\gamma}{1\ \mathrm{TeV}}\right)^{-1} \quad \mathrm{erg\ s^{-1}}. \tag{11}$$

The integrated IR luminosity implied by eq. (11) would presumably be larger. Condition (11) is satisfied in most cases. A central continuum source, if present, would also contribute a pair production opacity. The IR emission may arise from a cold accretion disk or dust reprocession, and is likely to originate from small radii, of order 10 to 100 R_g in these low luminosity objects. Adopting a size of 10 times the gravitational radius of a $10^{10} M_\odot$ black hole for the IR emission region, we find that the TeV flux will be strongly attenuated if the corresponding IR luminosity exceeds $\sim 10^{40}(\epsilon_\gamma/1\ \mathrm{TeV})^{-1}$ ergs s^{-1}. This is slightly below the luminosity inferred for low-luminosity AGNs [17], and comparable to upper limits on the luminosity of the point source in elliptical galaxies [18].

In conclusion, it has been shown that particles accelerating near the horizon of a spinning suppermassive black hole threaded by externally supported magnetic field lines, suffer severe energy losses through curvature emission. The curvature losses limit the maximum energy attainable by light nuclei to values well below that imposed by the voltage drop. The major fraction of the energy extracted from the rotating hole is radiated in the TeV band, with a rather hard spectrum that extends well beyond 10 TeV. Given the energy flux of cosmic rays above 10^{19} eV, as reported recently by current CR experiments, and an estimate of the density of supermassive black holes in the universe, it is concluded that if dormant AGNs are the sources of the ultra-high energy cosmic rays, then they should be detectable by current TeV experiments.

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